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Theoretical, on-ground and in-flight study of the Metis coronagraph vignetting

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ABSTRACT

On-board the Solar Orbiter ESA/NASA mission there is Metis, a coronagraph designed to study the solar corona by providing an artificial solar eclipse. Metis features two channels working at the ultraviolet Lyman-α (121.6 nm) and in the visible light (580-640 nm). On-ground, the Metis radiometric performance has been tested using a flat-field panel (uniform illumination); the stability of the performance can be verified in-flight through the analysis of the stars passing in the Metis Field of View.

Care must be taken to ensure the quality of the calibration, both before launch and for the long period associated with the space mission lifetime. For this reason, we are carrying out long period research of stars that cross the Field of View of Metis.

In this paper, we describe the vignetting function acquired: on-ground, simulated via a raytracing code and in-flight derived from on-ground measurements (performing some adjustments to account for the real Metis flight configuration). These vignetting functions are then compared with the vignetting data derived from the passage of the star Theta Ophiuchi in March and December 2021.

Keywords: Calibration, Coronagraph, Vignetting function, Theta Ophiuchi, Visible Light, Solar Orbiter

1. INTRODUCTION

From the ground, without the help of specific equipment the dim solar coronal light can be observed only during solar eclipses. To study the solar corona, not just during the solar eclipses, Bernard Lyot created the coronagraph [1]: a telescope that blocks the photospheric light of the Sun and lets pass that from the corona. A lot of coronagraphs are mounted on board spacecraft (S/C) because their acquisitions on the Earth suffer from some factors, such as Rayleigh scattering from the sky and the dependence on atmospheric conditions.

One of the most important solar missions is the Solar and Heliospheric Observatory (SOHO) launched in December 1995, and still working. On board SOHO there is the coronagraph LASCO (Large Angle and Spectrometric Coronagraph

Experiment) [2]. Being one of the longest-lived telescopes, a particularly interesting part of the work made by Morrill [3] on the LASCO C3 coronagraph concerns re-study the calibration of the instrument on-ground and after 8 years of the mission. Following his example, we considered studying the evolution of the calibration performance for the coronagraph Metis on board the Solar Orbiter**,** focusing, in particular, on the vignetting function.
Metis was launched in February 2020 on-board Solar Orbiter, the first solar mission that will reach a minimum distance from the Sun of 0.28 AU, and an angle with the ecliptic of 24°, during the nominal mission.
Despite Metis being a very recent coronagraph, we decided to apply the study of Morrill and to implement it with the new information every year. The star that we used for the study of the vignetting is Theta Ophiuchi, a warm star with a spectral class B2IV, a peak of the emission in the UV, with an apparent magnitude of 3.3 and placed 436 light years far from Earth [4]. Theta Ophiuchi passed twice in the Metis coronagraph field of view: in March and December 2021.
The Metis coronagraph is described in the next section, while the third section is dedicated to its on-ground radiometric calibration. The results on the vignetting function are presented and discussed in the fourth section.

2. METIS

Metis will observe the Sun as close as 0.28 AU, so it is important to reduce the extremely high thermal load, therefore an Inverted Externally Occulted configuration is used to block the light of the solar disk. Indeed, to reduce the thermal load, the light of the photosphere enters in Metis through the Inverted External Occulter (IEO) and is then rejected towards the entrance aperture by the mirror M_0 that is acting as an occulter as drawn in Figure 1.

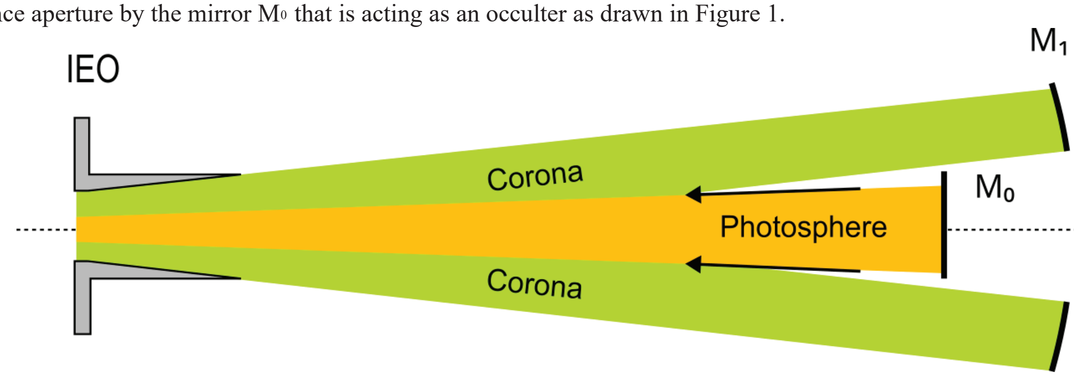


Figure 1 Schematic view of the Metis occultation concept. The light from the solar disk (dark yellow) is back rejected by the mirror M_0. The light of the corona (green) passes and enters inside the coronagraph.

In the following paragraph, the components of the Metis coronagraph, illustrated in Figure 2, are presented following the optical path of the incoming solar light.

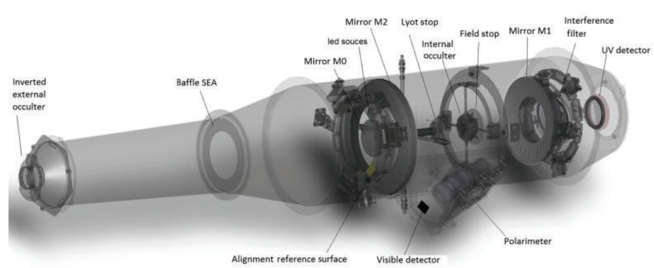
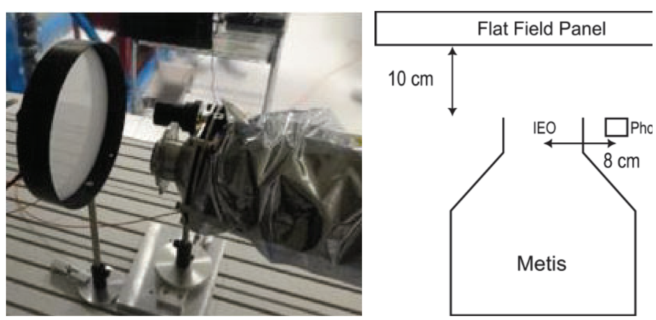


Figure 2 CAD of Metis coronagraph.

The photospheric light is not totally rejected out by mirror M_0. Indeed, some diffused light in the tube between IEO and M_0 may pass into the rest of the coronagraph. To minimize it, the tube is black coated, and a Shield Entrance Aperture (SEA) diaphragm is introduced. The coronal light is reflected by mirror M_1 towards mirror M_2, which also induces diffused light from real images of the edges of the IEO and the M_0 mirror. Therefore, an internal occulter (IO) and a Lyot Stop (LS) are respectively introduced, the rest of the diffused light being blocked by a Field Stop (FS). Then, the coronal light is reflected by mirror M_2 in the direction of the dichroic beam-splitter, the Interferential Filter (IF). The IF is optimized for narrowband spectral transmission in the ultraviolet (UV, 121.6 nm, H I Lyman-α) and broadband spectral reflection in the visible (VL, 580–640 nm).
The visible light reflected by IF enters in a polarimetric unit dedicated to perform measurements of the polarization of the coronal radiation. The coronal light passes through a sequence of optical elements: an optical collimating system (CD collimating doublet), a bandpass filter (BP), a linear polarization analyzer and is focused on the visible channel detector (Visible Channel Detector Assembly, VLDA). The polarization analyzer consists of a quarter-wave plate (QWP), liquid crystal (LCVR, liquid crystals variable retarder - Electro-optical Polarization Module Package, PMP), and a linear polarizer (LP). In order to reduce the reflection effects, all the lenses have a single layer anti-reflection coating, the LP also has a MgF_2 coating, and the QWP a multi-layer AR coating [4].
On the other side, the UV light transmitted by the IF arrives on the UV Detector Assembly (UVDA). Both channels have a CMOS sensor, a 1024 x 1024 pixel matrix for the ultraviolet, and a 2048 x 2048 pixel matrix for the visible [5].

3. ON GROUND MEASUREMENTS SET UP

Any instrument, in fact needs on-ground calibration prior to the launch. For the Metis coronagraph, the calibration has been based on a flat-field panel source to simulate homogeneous illumination.
The flat field panel, a Spike-a^{TM} flat fielder, was composed of a LED matrix with several layers of diffusing material to obtain a quasi-uniform illumination. This matrix of 9V-powered LEDs was put in the center of aperture of Metis (lower voltage can induce temporal fluctuation of the luminosity), which was set perpendicular to the optical axis of the telescope as shown in Figure 3 a.
In Figure 3 b, the experimental scheme is represented: the flat field panel was positioned 10 cm from the Metis aperture, and a photodiode was set 8 cm from the centre of the IEO to check the flat field panel illumination performance.



(a) (b)

Figure 3 (a) Optical layout of Metis in the laboratory calibration test set-up. (b) Diagram of the top view of the flat field panel, of the photodiode and of Metis with relative distances.

The photodiode (model AXUV100G) measured the irradiance of the flat field panel, with an internal quantum efficiency of 100% [8]. As represented in Figure 4, in front of the photodiode there was a bandpass filter, provided by OPTEC (Optical and Optoelectronic systems). The filter (10 mm x 10 mm) is optimized for the visible wavelength: 580-640 nm. The responsivity provides a quantitative indication of how much current is generated from each Watt of incident power.

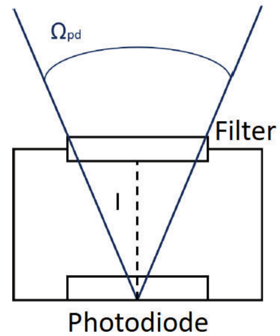


Figure 4 Scheme of the photodiode and filter.

The images were produced in a series of four frames, with different times of exposure. For our purpose, we used those with an exposure time of 100 s. The images were dark and bias subtracted, and we calculated the vignetting function. The analysis of the vignetting function on ground was reported in the ICSO 2020 [9].

4. IMAGE ANALYSIS

During the integration and calibration, the IO and the IF were moved respectively to reduce the stray light and adjust the focus position on the visible focal plane. The vignetting function measured on-ground was taken after these adjustments, and is shown in Figure 5 a. The simulated vignetting image used for this work was produced by using Zemax, a ray tracing software. We built the Metis telescope theoretical model, with all the optical elements perfectly aligned, and then, using the Zemax function "geometric image simulation", the simulated vignetting function image shown in Figure 5 b has been computed.

After launch, during the in-flight commissioning, IO was repositioned to remove an increased value of stray light. For this reason, a new vignetting image was created and is shown in Figure 5 c. To obtain the in-flight vignetting function, the on-ground image was re-centered using a method based on the use of the isophotes. The recentering method is described in [10].

All the images in Figure 5 are oriented with the solar north up.

The image shown in Figure 6 is an image acquired by the Metis coronagraph in March 2021 with a 20s exposure time. The Theta Ophiuchi star is in the orange box - a zoom of this region is shown on the left in the same figure.

In the images of Figure 5 the orange line represents the direction along which we plotted the vignetting for the first star passage.

The images were acquired at different exposure times (20s and 30s) and different distances from the Sun. Theta Ophiuchi passed twice in front of Metis so the sessions of Short-Term Planning (STP) [8] taken into account are: STP-140 and STP-182. In the first case, the images were acquired on 25/03/2021 and the distance between Solar Orbiter and the Sun was 0.72 AU, in total brightness at 35°, while STP-182 was taken on 20/12/2021 with a distance of 1.01 AU, with polarized brightness at 35°.

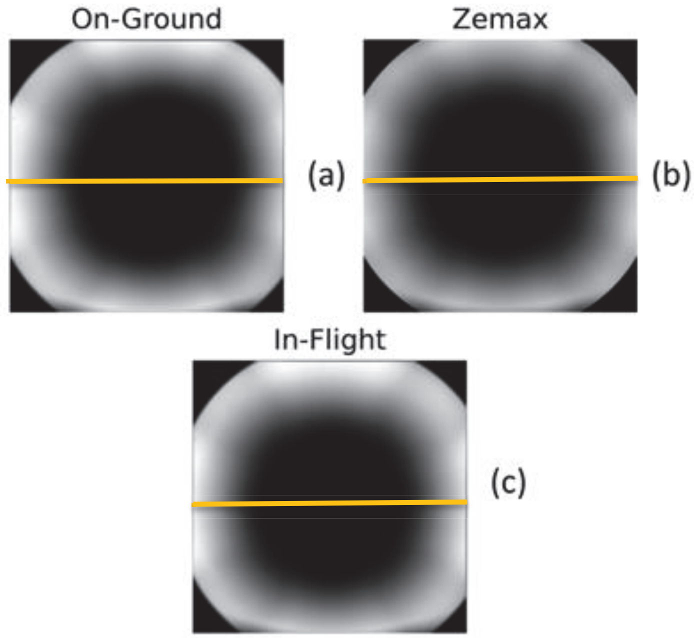


Figure 5 Images of the vignetting function acquired on-ground (a), simulated by Zemax (b), adjusted in-flight (c). The orange lines are the position of the plot of the vignetting.

Theta Ophiuchi passed through the rows 1017 ± 2 pixels in the first passage and 615 ± 2 pixels for the second. To study the vignetting function we took a box with the dimensions of 10 pixels x 10 pixels around the star. We evaluate the mean values for other 4 adjacent boxes, with the same dimensions, at the right, left, top and bottom next to the star bounding box. These values have background information like the solar corona or the zodiacal light. The mean background values have been subtracted from those measured in the star bounding boxes.

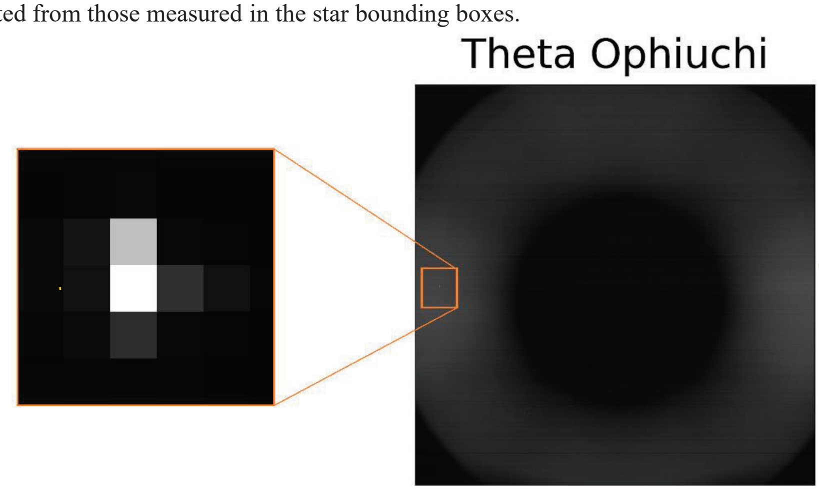
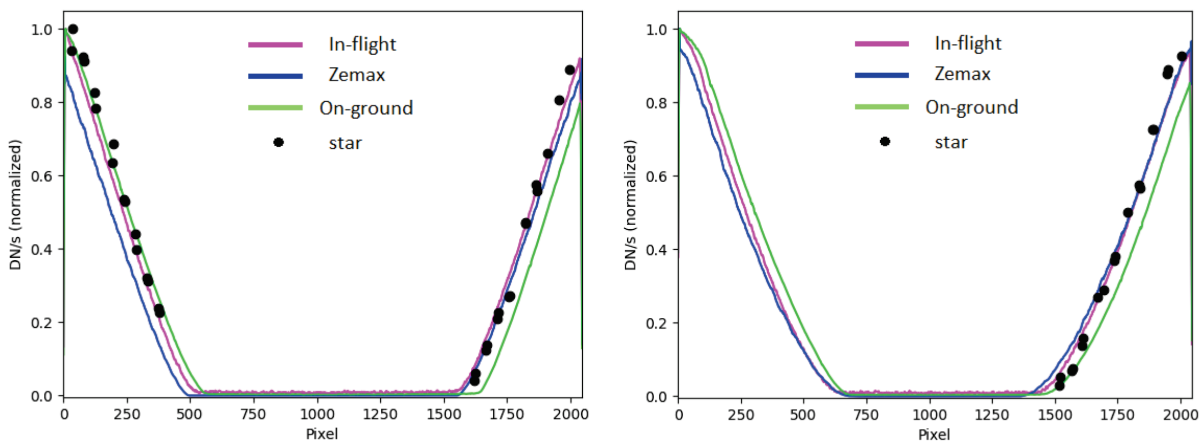


Figure 6 Image acquired in March 2021, Theta Ophiuchi is in the orange box. A zoom of the star is on the left in a box of 10 x 10 pixels.

In Figure 7, we plot the intensities for different vignetting functions: in-flight; on ground; simulated with Zemax, and derived from Theta Ophiuchi first (Figure 7 a) and second passage (Figure 7 b). All the plots are normalized to their maximum intensity.
In the first case, the star passed all over the detector whereas in the second not all data were analyzed, we have Theta Ophiuchi just on the right side of the detector.
In both cases the vignetting function profile derived from the star transit is in agreement with the one evaluated in-flight (magenta line) - average difference around 10%. As expected, there is a shift between the in-flight and on-ground vignetting function due to the recentering process applied to obtain the in-flight vignetting function [10]. The simulated Zemax vignetting has a good agreement with the in-flight vignetting in the left part of the frame, but not in the right one, because it doesn't consider the movement of the IO and the IF performed during the instrument alignment on-ground.



(a) (b)

Figure 7 Comparison of the different derived vignetting functions: vignetting in-flight, simulated with Zemax, measured on-ground and stellar in-flight. In (a) the plot for the first star passage in march (row 1017) and in (b) for the second in december (row 615).

5. CONCLUSIONS

We replicated the study of Morrill [3] for the assessment of the vignetting function evolution during the mission lifetime in-flight. For obtaining the in-flight information we used a star, Theta Ophiuchi. We presented the experimental set-up used for the on-ground vignetting function evaluation, and we compared it to in-flight and simulated vignetting and to the intensity of the star acquired. As we expected, since the mission is recent (2 years), the agreement with the vignetting function is good. In both the star crossings, the data obtained with the star are in optimal agreement with the expected in-flight vignetting function.
This work can be updated year after year to study the evolution of vignetting. Although in LASCO C3 there wasn't any variation, Metis coronagraph is the first mission that is going as close to the sun and outside the ecliptic plane, then every change and evolution must be studied. It can be of interest for future solar missions as a case study.

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